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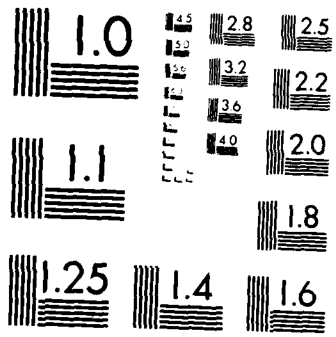

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FINAL REPORT

TURBULENT BOUNDARY LAYERS DEVELOPING OVER COMPLIANT SURFACES

By

S. G. Lekoudis and T. Sengupta

Prepared for

THE OFFICE OF NAVAL RESEARCH
COMPLIANT COATING DRAG REDUCTION PROGRAM

Under

Contract ONR N00014-82-K-0271
(Georgia Tech Research Institute E-16-699)

May 1983

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332

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SUMMARY

This report summarizes work done under the ONR Contract No. N00014-82-K-0271 to Georgia Tech, between March 1, 1982 and March 1, 1983. The objective of this research program was to develop prediction techniques for high Reynolds number turbulent flows over compliant surfaces. This objective was pursued by evaluating the wall induced Reynolds stresses using solutions of the linear momentum equations.

One graduate student, Mr. Tapan Sengupta was the research assistant in this program. He is currently a Ph.D. candidate at the School of Aerospace Engineering at Georgia Tech.

1. INTRODUCTION

The problem of reducing drag due to skin friction remains of interest. This is the case because of the significant benefits that would result from an application of a drag reducing scheme on airplanes, ships or underwater vehicles. One of the techniques that have been proposed for such a scheme is wall compliance. Wall compliance could, in principle, work in two ways: either it could delay transition, or it could modify the inner part of a turbulent boundary layer so that reduced skin friction would result.

The Office of Naval Research supports an ongoing program in compliant surfaces for drag reduction. The program consists of analytical and experimental studies with the goal of inventing a working system (Reference 1). The prime candidate for such a system is the turbulent boundary layer developing on a surface with desirable properties. Therefore, the center of attention in this research is the interaction of the turbulent boundary layer with a compliant coating.

Any prediction method that attempts to compute high Reynolds number flow over compliant surfaces aims at predicting unsteady turbulent flow. Therefore some credibility of the method must be established by using it to predict steady turbulent flows over rigid wavy surfaces. There are measured data for such flows (References 2, 3, 4, 5). Such flows do not show any beneficial drag reduction. The reason is that although the average skin friction is lower than that for the equivalent flat plate flow, the phase shift of the pressure results in a net drag increase.

The developed prediction technique and results for both stationary and moving wavy surfaces are presented and discussed in the next sections of this report.

2. THE TWO-DIMENSIONAL TURBULENT BOUNDARY LAYER OVER A STATIONARY WAVY WALL IN INCOMPRESSIBLE FLOW

The coordinate system used (Figure 1) is boundary-conforming. This is very important because the linearized wall boundary condition (transfer at the mean interface) presents serious errors for wave amplitudes that are large compared to the turbulent sublayer thickness, if a cartesian system is used (Reference 6). This error was numerically verified by working with a cartesian system and predicting turbulent separation for the unseparated flow of Reference 5. The coordinate system is frozen in space, if one moves in the positive x-direction with the wave velocity c (zero for the rigid wall case). Contrary to the coordinate systems used in References 6 and 7, the present system has no singularities away from the wall and approaches a cartesian system far from the wall. The normalizing parameters are the local boundary layer displacement thickness δ^* and the local freestream velocity U_e^*. The nondimensional wave amplitude ϵ is supposed to be small for the analysis to be valid. For the data of Reference 5 it is more than 1, but this did not seem to invalidate the calculations. It was found, by trial and error, that for the same data the integration normal to the wall has to extend about $18\,\delta^*$ before the freestream boundary conditions are appropriately applied.

The velocity (Figure 1) components u, v in the S, N, directions respectively are decomposed into three parts: a mean time-independent part, a random part and a periodic in space and time part. For example, the u-velocity component is written as

$$u = \bar{U}(N) + u'(s, N, z, t) + \epsilon\left[\tilde{u}(N)e^{ik(s-ct)} + \tilde{u}^*(N)e^{-ik(s-ct)}\right] \qquad (1)$$

In Equation (1) stars denote complex conjugates. Time-averaging the Navier-Stokes equations for incompressible flow results into stresses due to the

random component and to the periodic component of the velocity (References 9, 10). The last stresses are termed wave-induced stresses. Taking a phase average of the Navier-Stokes equations, subtracting the time-averaged equations, neglecting terms of order ϵ^2 and assuming that the difference between the time-averaged stresses due to the random velocity component and the phase-averaged stresses due to the same velocity component is small, we obtain an Orr-Sommerfeld system for the periodic part of the flow.

The Orr-Sommerfeld system is nonhomogeneous because of the terms due to curvature, with homogeneous boundary conditions (References 8, 9, 10). The numerical difficulties associated with such systems are taken care of with the use of standard methods (Reference 11). It was found that, in general, the Orr-Sommerfeld problem for a turbulent mean profile is stiffer than the same problem for a laminar profile. The reason is not the Reynolds number but the profile shape. The mean turbulent flow is solved using a finite-difference technique, the Keller-box, for two-dimensional incompressible flow with arbitrary pressure gradients.

The computed pressure and skin friction variations were compared with measured data. A point has to be made about the stresses from the random component of the velocity. If these stresses remain unexpanded in the perturbation scheme, the agreement with measured data is not as good, especially for the skin friction distribution (References 8, 9). The model used in References 2, 3 and 6 proved adequate. Navier-Stokes simulations of these steady turbulent flowfields (References 4 and 12) indicate that the algebraic eddy-viscosity is adequate. This model is used for the mean flow calculations.

Comparisons for pressure and skin friction distributions are shown in Figures 2, 3, and 4. The measurements are from Reference 5 for the Figures 2 and 3 and from Reference 4 for Figure 4. No detailed skin-friction measurements are

available for the flows described in Reference 4. The agreement between calculations and measurements is good. It should be emphasized that good agreement with measured pressures is not very hard to achieve, even simpler theories show good qualitative agreement. The skin friction is a much more difficult quantity to predict for such flows.

The linear theory can provide estimates of the pressure drag, but not of the skin friction drag. This is because to $O(\epsilon)$ the periodic variation of the skin friction produces no net effect on the drag. However it is experimentally established that the mean skin friction of these flows is lower than that of the flat plate (Reference 4). This is the reason such flows were examined. To predict the average skin friction, we used a nonlinear theory (Reference 9). The boundary layer equations used to obtain the mean flow $\bar{U}(N)$, contain wave-induced stresses. These stresses are:

$$\frac{\epsilon^2}{4}(\tilde{u}\,\tilde{v}^* + \tilde{u}^*\tilde{v}) \qquad (2)$$

and they are functions of N only. Stars in Equation (2) denote complex conjugates. The wave-induced stresses described in Equation (2) represent essentially a streaming effect. The boundary layer equations were solved including these stresses in an iterative fashion. The iterations were between the meanflow solution and the solution of the Orr-Sommerfeld system (Reference 9). No more than 5 iterations are needed to obtain a converged solution. The following observations can be made from this solution.

The mean flow is slightly modified only close to the wall with a resulting reduction in the skin friction. Figure 5 shows the skin friction distribution for the experimental setup of Reference 4. The calculations predict that the skin friction is lower than that of the flat plate, in agreement with experimental observations. The iterative scheme has a very small effect on the amplitude and the phase shift

of the pressure and the shear on the wavy wall. The predicted drag was compared with the data from NASA-Langley (Reference 4). For the wave with $h/\lambda = .015$ (Reference 4), the ratio of the pressure drag over the flat plate drag was computed to be 0.234 and the same ratio for the skin friction drag was 0.985. The agreement is comparable with the one obtained from solutions of the full Navier-Stokes and in excellent agreement with the measurements (References 4, 9). The code used to generate these predictions takes about one hour of CDC 6600 time for the 35 sinusoidal waves of the experimental setup of Reference 4.

3. THE TWO-DIMENSIONAL TURBULENT BOUNDARY LAYER OVER A MOVING WAVY WALL IN INCOMPRESSIBLE FLOW

For simplicity, a cartesian system was used to solve the Orr-Sommerfeld system for the case of a wall translating in the flow direction with nondimensional velocity c. Details from this calculation are given in Reference 8. Because of the coordinate system, the wavy wall of Reference 5 was reduced to 1/10 of its amplitude, and then used in the moving wall calculations. The Orr-Sommerfeld system predicted flow separation for the original wave by calculating a periodic skin friction with amplitude larger than the mean skin friction. Very little change in the phase of the shear and the pressure variations resulted from the wall motion. Therefore the linear theory indicates that the only favorable effect from a moving wall is the reduction of the pressure drag because of the reduction of the amplitude of the oscillating pressure (Reference 8). The calculations were repeated for a boundary layer with a pressure gradient. Again no significant changes from the stationary wall case of the phase shift of the pressure and the shear variations were found (Reference 8).

Solutions for the nonlinear problem were also computed. The skin friction distribution, for the experimental setup of Reference 4, for nondimensional wall velocities, of 0.1 and 0.2 are shown in Figure 5. The wavy wall skin friction is slightly lower than that for the flat wall that moves with the same velocity, as expected. The pressure coefficients are shown in Figure 6.

4. THE COMPLIANT WALL PROBLEM IN TWO AND THREE DIMENSIONS

The previous two sections in this report deal with the case of stationary wavy walls, or walls that translate with uniform velocity. In this section the use of the coordinate system for the calculation of compliant wall motion is described.

For the two-dimensional problem, the absolute velocities u, v in an inertial cartesian (x, y) coordinate system, on the surface of the wave, N = 0, are (Reference 9):

$$u = \bar{U} + u' + c + \epsilon e^{ik(s-ct)} [\tilde{u} - k(\bar{U} + u') - ikv'] \tag{3}$$

$$v = v' + \epsilon e^{ik(s-ct)} [\tilde{v} - kv' + ik(\bar{U} + u')] \tag{4}$$

where the velocities in the RHS of these equations are all relative to the curvilinear S, N, Z coordinate system. For the case of a translating wall, u = c and v = 0, as it should be, because $\bar{U} = \tilde{u} = \tilde{v} = u' = v' = 0$ on the wavy surface.

For a compliant surface $\bar{U} = -c$, $u' = v' = 0$, and therefore

$$\tilde{u} = \frac{u}{\epsilon e^{ik(s - ct)}} - kc \tag{5}$$

$$\tilde{v} = \frac{v}{\epsilon e^{ik(s - ct)}} + ikc \tag{6}$$

For a compliant wall that admits traveling wave solutions u and v are multiples of $e^{ik(s-ct)}$ with coefficients that are related with the wall compliance. Since we are not solving the eigenvalue problem (i.e., material properties of the wall are neglected) we can prescribe u and v at will. In this case the Orr-Sommerfeld system has inhomogeneous boundary conditions as well. Calculations for such a system will be reported in Reference 9.

The three-dimensional problem can be more complicated than it appears. The reason is that the direction of the wave motion and the direction of the phase

of the wavy surface do not have to coincide (Figure 7). A coordinate system that moves with the wave and has all the desirable properties of the one used in the two-dimensional problem is constructed in Figure 7. Then the velocity components in the S, N, Z' curvilinear system can be expanded as follows:

$$u = \bar{U}(N) + u' + \epsilon\left[\tilde{u}\, e^{ik(s - c_1 t)} + \tilde{u}^*\, e^{-ik(s - c_1 t)}\right] \quad (7)$$

$$v = v' + \epsilon\left[\tilde{v}\, e^{ik(s - c_1 t)} + \tilde{v}^*\, e^{-ik(s - c_1 t)}\right] \quad (8)$$

$$w = \bar{W}(N) + w' + \epsilon\left[\tilde{w}\, e^{ik(s - c_1 t)} + \tilde{w}^*\, e^{-ik(s - c_1 t)}\right] \quad (9)$$

where $\bar{U}$ and $\bar{W}$ are the projections of the two-dimensional mean velocity profile on the xy and yz axis, respectively. The Navier-Stokes equations and the Equations (7), (8) and (9) give another nonhomogeneous Orr-Sommerfeld system, because of the terms due to curvature. For the case of a wavy wall, translating with velocity c in the x-direction ($\theta = 90^{\circ}$) the boundary conditions are homogeneous. The nonlinear problem can be solved by finding the wave-induced stresses in the plane of the mean flow, which is not specified in Figure 7 and is also arbitrary. This can be done by velocity decomposition once the solution from the Orr-Sommerfeld system is known.

For the case of compliant walls, equations analogous to (6) and (7) can be derived. The equations and calculations of such flows will be reported by the authors of this report.

5. CONCLUDING REMARKS

Two-dimensional turbulent boundary layers, in incompressible flow, over wavy surfaces have been investigated. The solution of the linear momentum equations, reduced to a nonhomogenous Orr-Sommerfeld system, have been obtained. They have been used to model the wave-induced stresses in the time-averaged boundary layer equations. The calculations predict a small reduction of the mean skin friction, in agreement with experimental observations, for the case of stationary wavy walls. This reduction persists when the wavy wall is translating downstream with uniform velocity, while the pressure drag is decreased.

6. PUBLICATIONS AND PRESENTATIONS

Based on work supported from this contract, the following publications and presentations resulted:

1. "Calculation of Turbulent Boundary Layers Developing Over Compliant Surfaces," by T. Sengupta and S. Lekoudis, presentation at the Drag Reduction Symposium, in the National Academy of Sciences (Washington, D.C., September 13-17, 1982), sponsored by ONR, NASA, AFOSR and NSSC.

2. "Calculation of Incompressible Turbulent Boundary Layers Over Moving Wavy Surfaces," by T. Sengupta and S. Lekoudis, AIAA Paper 83-1670 (16th Fluid and Plasma Dynamics Conference, July 12-14, 1983).

7. REFERENCES

1. Abstracts of the Drag Reduction Symposium held at the National Academy of Sciences in Washington, D.C. on September 13-17, 1982 and sponsored by ONR, NASA, AFOSR, and NSSC.

2. "Influence of the Amplitude of a Solid Wavy Wall on a Turbulent Flow, Part 1, Non-Separated Flows," by D. P. Zilker, G.W. Cook and T.J. Hanratty, J. Fluid Mechanics, Vol. 82, Part 1, pp. 29-51, 1977.

3. "Influence of the Amplitude of a Solid Wavy Wall on a Turbulent Flow, Part 2, Separated Flows," by D.P. Zilker and T.J. Hanratty, J. Fluid Mechanics, Vol. 90, Part 2, pp. 257-271, 1979.

4. "Turbulent Drag Characteristics of Small Amplitude Rigid Surface Waves," by Lin, J.C., Walsh, M.J., Watson, R.D. and Balasubramanium, R., AIAA Paper 83-0228.

5. "An Experimental Investigation of the Turbulent Boundary Layer Over a Wavy Wall," by A. Sigal, Ph.D. Thesis, California Institute of Technology, 1971.

6. "A Comparison of Linear Theory with Measurements of the Variation of Shear Stress Along a Solid Wave," by C.B. Thorsnees, P.E. Morrisroe and T. J. Hanratty, Chemical Engineering Science, Vol. 33, pp. 579-592, 1978.

7. "Viscous Flow Drag Reduction," Progress in Astronautics and Aeronautics, (Paper by Cary, A.M., Weinstein, L.M. and Bushnell, D.M.), Vol. 72, 1980.

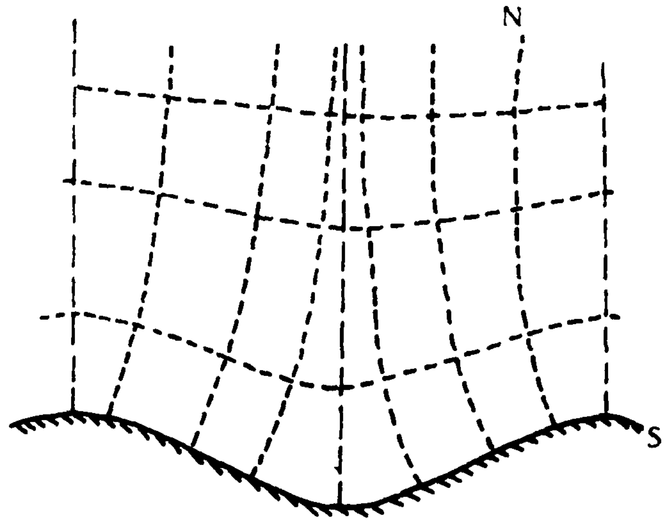
8. "Turbulent Boundary Layers Developing Over Compliant Surfaces," by S. G. Lekoudis and T. Sengupta, Progress Report on Contract N00014-82-0271 submitted to ONR in September 1982.

9. "Turbulent Boundary Layers Over Moving Wavy Surfaces," by T. Sengupta and S. Lekoudis, AIAA Paper 83-1670, 16th Fluids and Plasma Dynamics Conference, Danvers, Mass.

10. "Turbulent Boundary Layers Developing Over Compliant Surfaces," proposal submitted by the Georgia Institute of Technology to ONR in December 1980.

11. "Computational Solution of Linear Two Point Boundary Value Problems Via Orthonormalization," by M.R. Scott and H.A. Watts, SIAM Journal Numerical Analysis, Vol. 14, No. 1, 1977.

12. "Computation of Turbulent Flow Over a Moving Wavy Surface," by John McLean, Bulletin of the American Physical Society, Vol. 27, No. 9, 1982.



$$S = (x - ct) + \epsilon e^{-ky} \sin k(x - ct)$$

$$n = y - \epsilon e^{-ky} \cos k(x - ct)$$

Figure 1. The Coordinate System

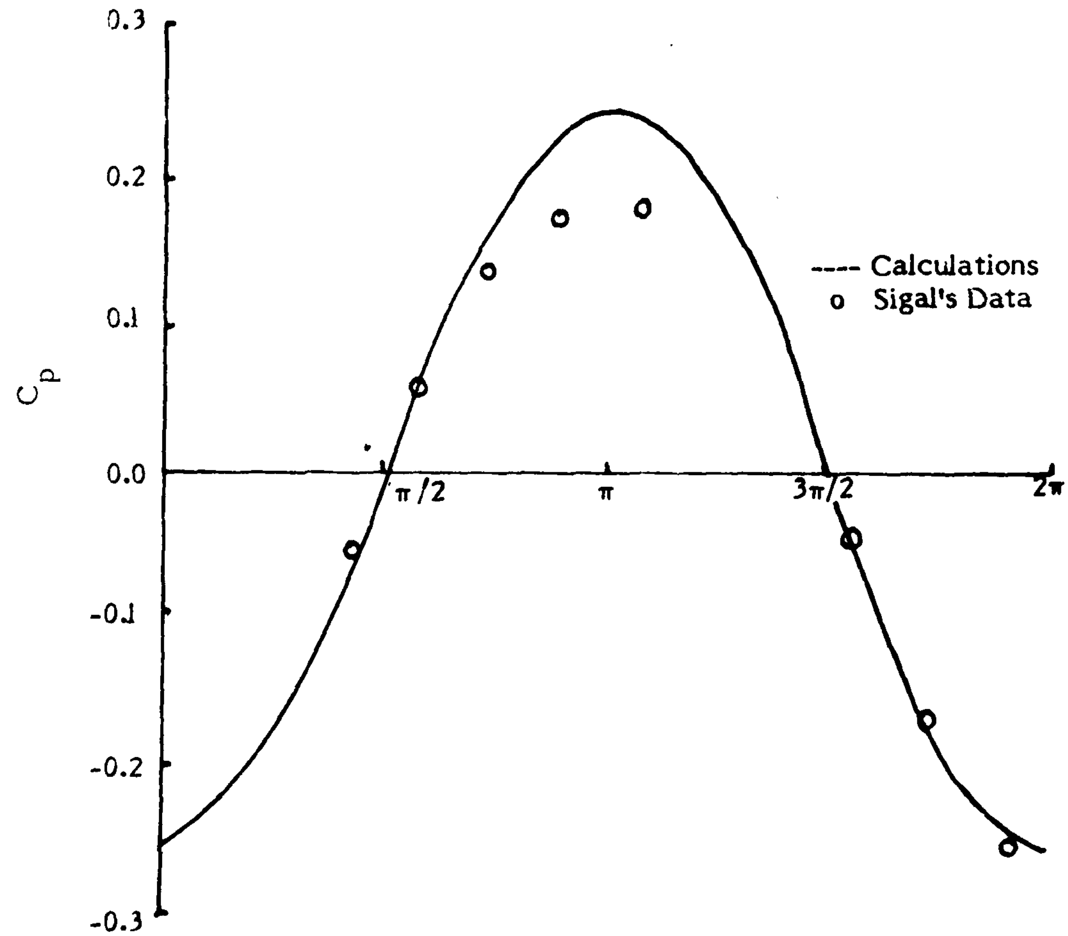


Figure 2. Comparison between calculations and measurements

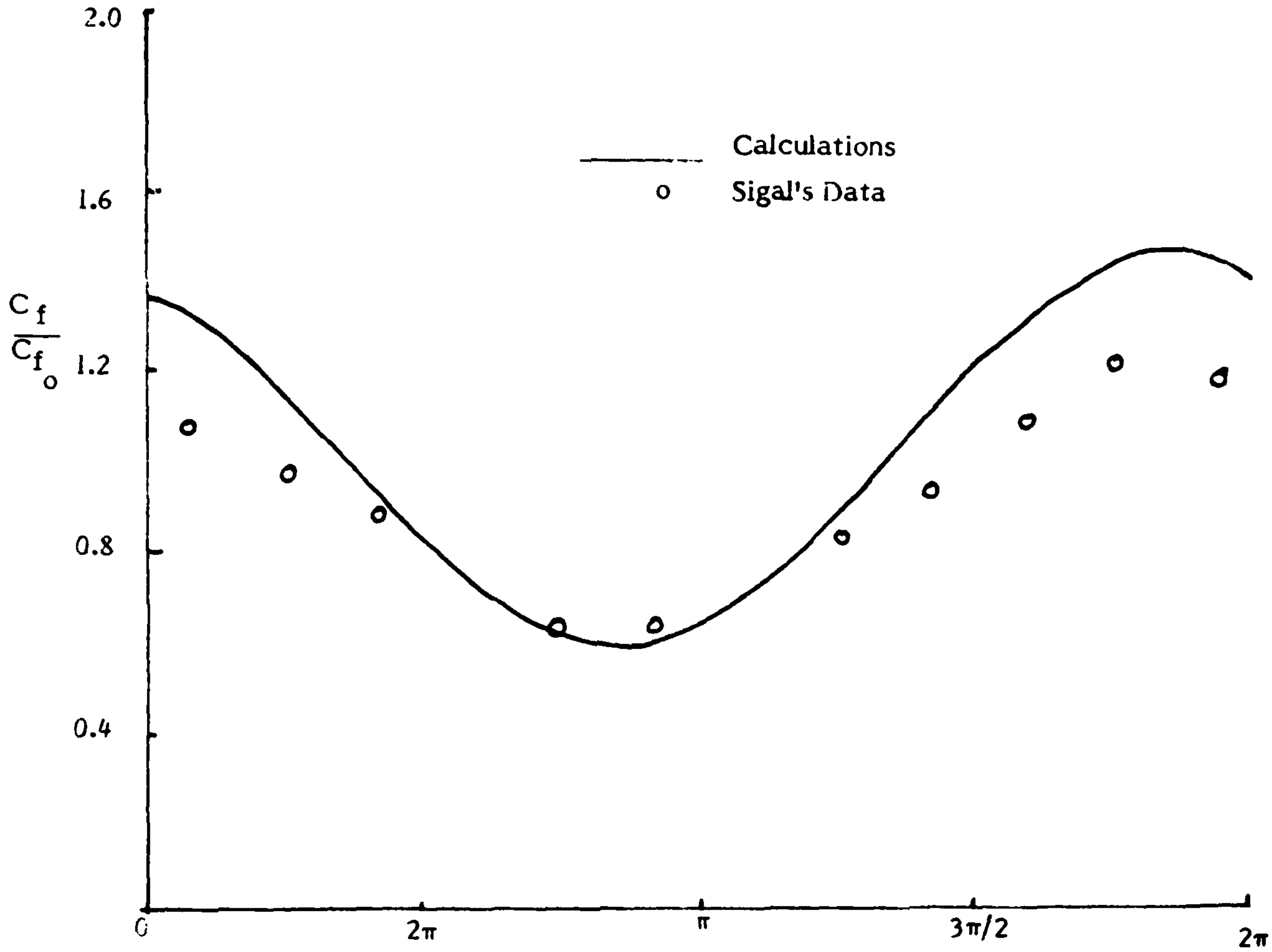


Figure 3. Comparison between calculations and measurements

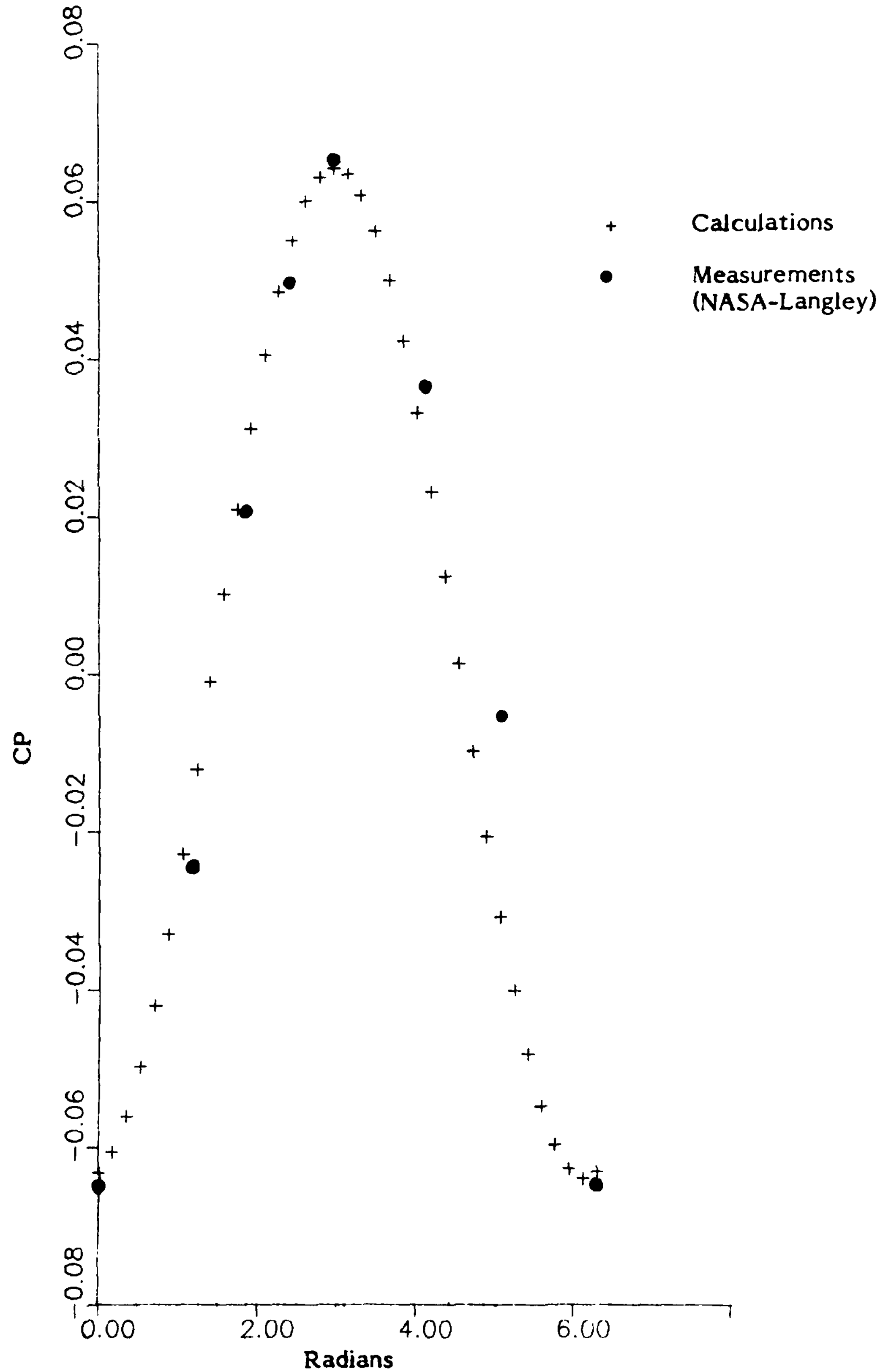


Figure 4. Comparison between calculations and measurements

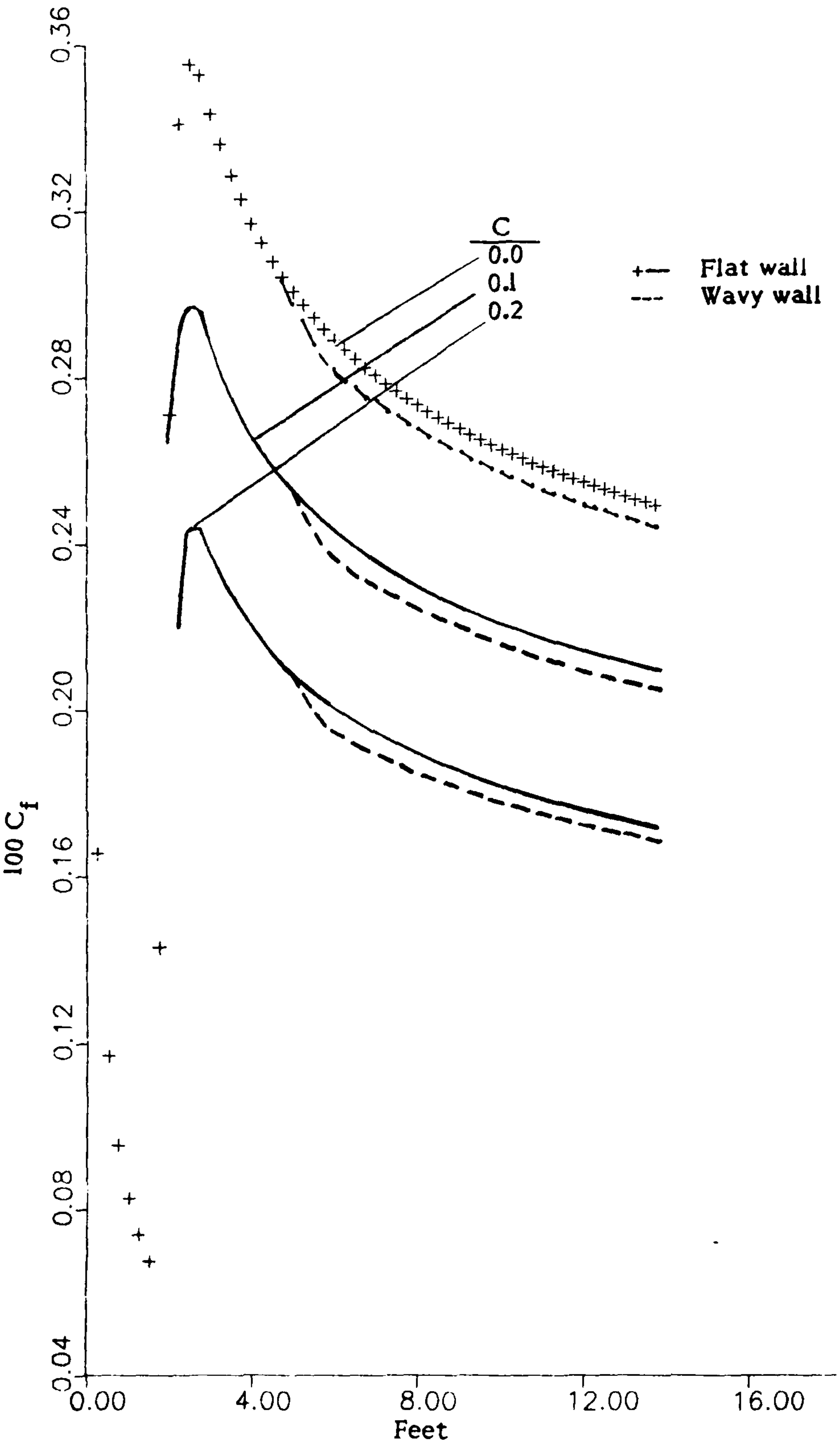


Figure 5. Mean skin friction predictions for the experimental set up NASA-Langley (Reference 4).

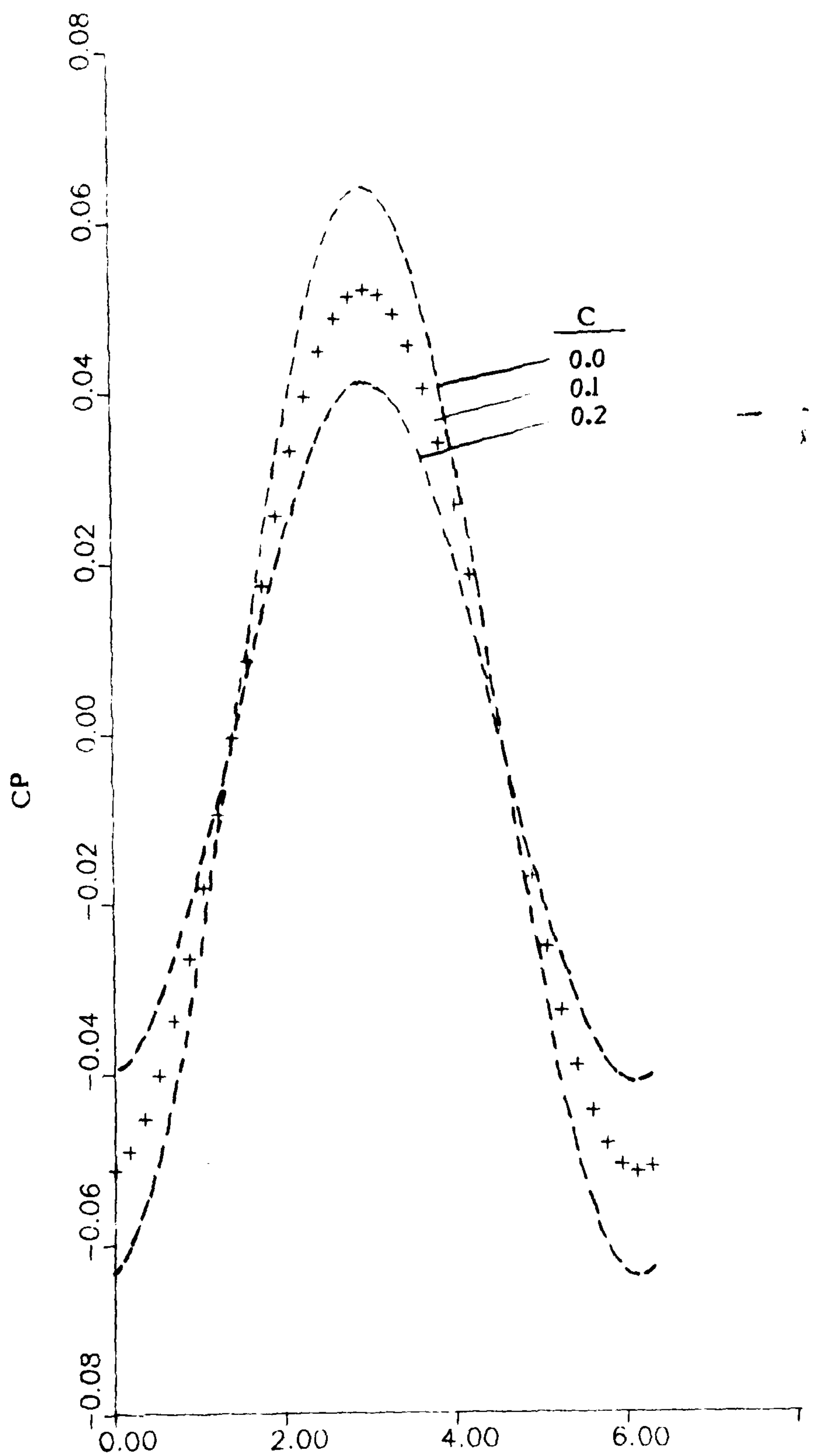


Figure 6. Predicted pressure distributions for the experimental set up of NASA-Langley (Reference 4)

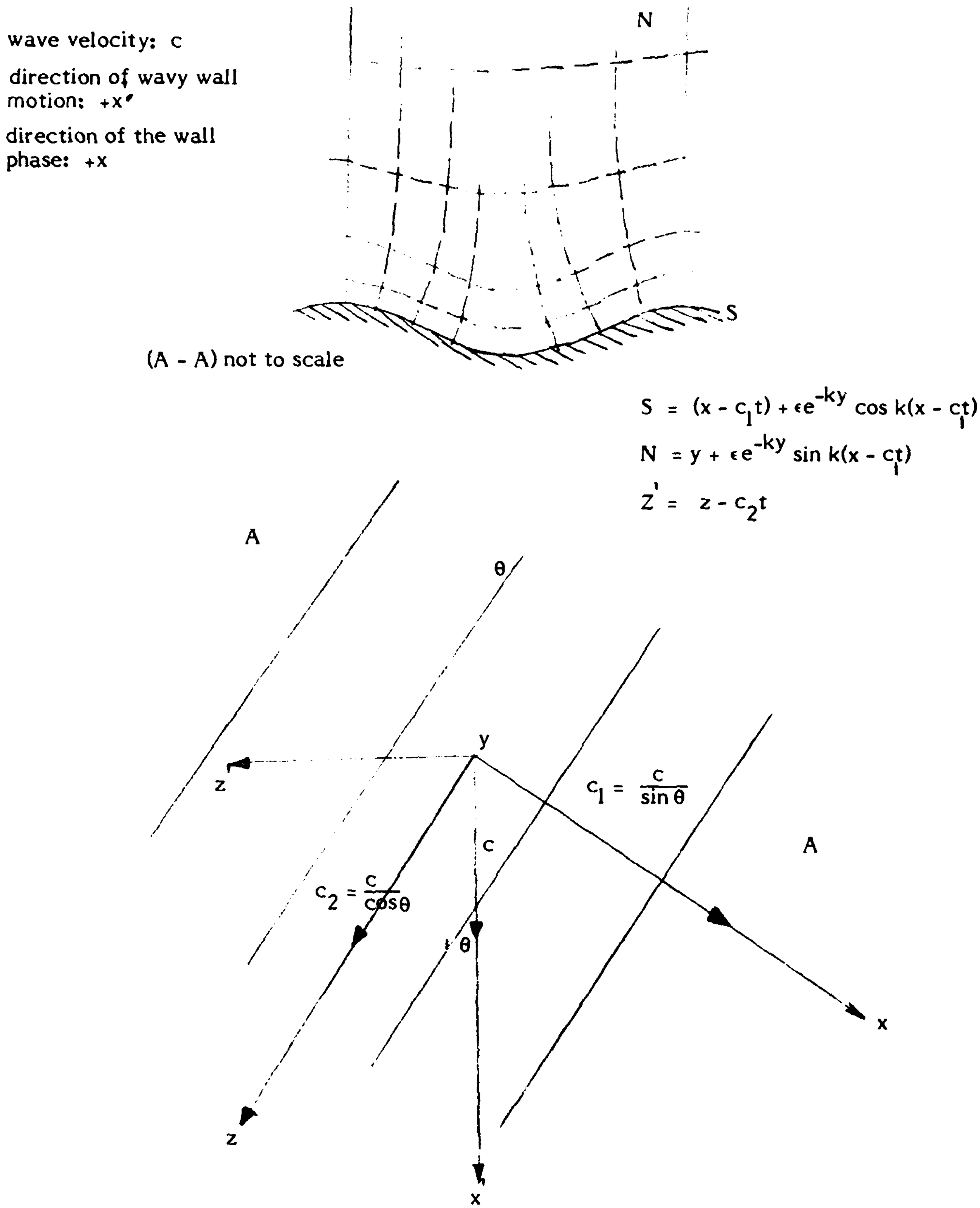


Figure 7. Coordinate system for the three-dimensional problem

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